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Assessment of forest climate and air pollution impacts in the western U.S. and the valley of Mexico

Paul Miller

Final LOI Report

Assessment of Forest Climate and Air Pollution Impacts in the Western U. S. and the Valley of Mexico

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Summary

A cooperative study was undertaken to compare the climates of the Valley of Mexico and the San Bernardino Mountains of southern California in relation to exposure to ozone air pollution. The nutrient status of pine foliage and the deposition of nitrogen and sulfur compounds were also measured in the Valley of Mexico. Observations were made at high and low pollution sites through collection and measurement of throughfall. Site nutrient status was evaluated from plant, soil and streamwater nutrient analysis. Results for climatic variables and ozone are presented for July through December 1995 following establishment of a new ozone monitor, weather station and data logging system at the Desierto de los Leones (DDLL). Ozone and weather data were collected simultaneously from a station at Barton Flats in the San Bernardino Mountains. Native pine species were used at each location as indicators of chronic ozone effects on crown condition. Black cherry proved to be an excellent bioindicator of ozone-induced foliar injury at DDLL. Differences in temperature and relative humidity at these locations could have an important effect

on ozone exposure response of pines and other vegetation. Nutritional data from pine foliage, soil and streamwater suggest that N deposition has enriched the nitrogen status at DDLL.

Introduction

The evaluation of impacts of ozone and associated nitrogen and sulfur compounds on forest ecosystems is a task requiring a multidisciplinary approach. Pollutant effects can be direct and immediate, as in the case of ozone, or indirect and gradual by influencing nutrient cycling and soil acidity by deposition of nitrogen and sulfur compounds. Climate conditions can have a strong influence on forest response to these pollutants. The intent of this study was to make comparable measurements of climate, pollutant exposure and tree response using similar methods at sites with different climates, in particular the Valley of Mexico and southern California. Preliminary comparisons have revealed some of the differences in the general seasonal climate and ozone exposure environments in the Valley of Mexico and the San Bernardino Mountains of southern California (Miller et al. 1994). No real time comparisons of nitrogen and sulfur deposition had been made. However, it was known that nitrogen deposition (primarily dry deposition) to terrestrial ecosystems in the Los Angeles region is among the highest in North America (Bytnerowicz et al. 1987, Fenn and Bytnerowicz 1993, Solomon et al. 1992). Preliminary wet and dry deposition measurements in the Valley of Mexico suggest that N and S deposition may both be of sufficient magnitude to alter nutrient cycling processes in nearby forests (Fenn and De Bauer, unpublished data).

The original proposal title was: "Assessment of forest air pollution impact in Western and Eastern U.S. Regions and in Central Mexico." The proposed budget was originally about $150,000 per year for FY95 and FY 96. After final negotiations the budget for FY95 and FY96 combined was about $50,000. The principal change in the scope of work was to limit the amount of work proposed for the Eastern U.S. by Penn. State U. cooperators. A small part of the shortfall was supplied by the normal appropriated funds of our Research Work Unit.

Methods

The location of the monitoring site for ozone and climate was at the Parque Cultural Y Recreativo Desierto de los Leones (DDLL). This heavily used recreational site is now known by the Mexican public as an area suffering tree damage from the air pollution transported from Mexico City about 25 km to the NE (Figure 1). Ozone injury symptoms are present on the foliage of *Abies religiosa* (Mexican religious fir), *Pinus hartwegii, Pinus montezuma* and *Prunus serotina* var. *capuli* (black cherry). The San Bernardino National Forest is about 100 to 150 km east of the Los Angeles metropolitan area (Figure 1). Mixed conifer forest is the most important forest type with ozone injury to *Pinus ponderosa* and *P. jeffreyi*.

First we concluded the Letter of Intent (LOI) agreement with INIFAP-SAGAR, Centro Nacional de Investigacion Disciplinaria en Conservacion y Mejoramiento de los Ecosistemas Forestales. Then we established separate cooperative agreements with the Colegio de Postgraduados at Montecillo, MX and with the Department of Plant Pathology at Penn State University.
The first task was to upgrade the equipment for the ozone and weather station at the DDLL. This was a three step process involving first, familiarization and training with the equipment for Abel Quevado during a 3 day visit to Riverside, second the shipping of the equipment to Mexico City and third the establishment of the equipment in working condition at the DDLL. With the exception of the equipment being seized by customs officials and held for 6 months, requiring an additional fee to release it back to the U.S. and an additional cost to ship it to Mexico again in diplomatic pouch, the procedure was completed. The new station consisted of a DASIBI ozone continuous monitor, a Campbell data logger and the meteorological sensors required to measure winds, temperature, relative humidity and photosynthetically active radiation (PAR). Data gathering began in July 1995 and data for July-December 1995 was sent to Riverside via the internet.

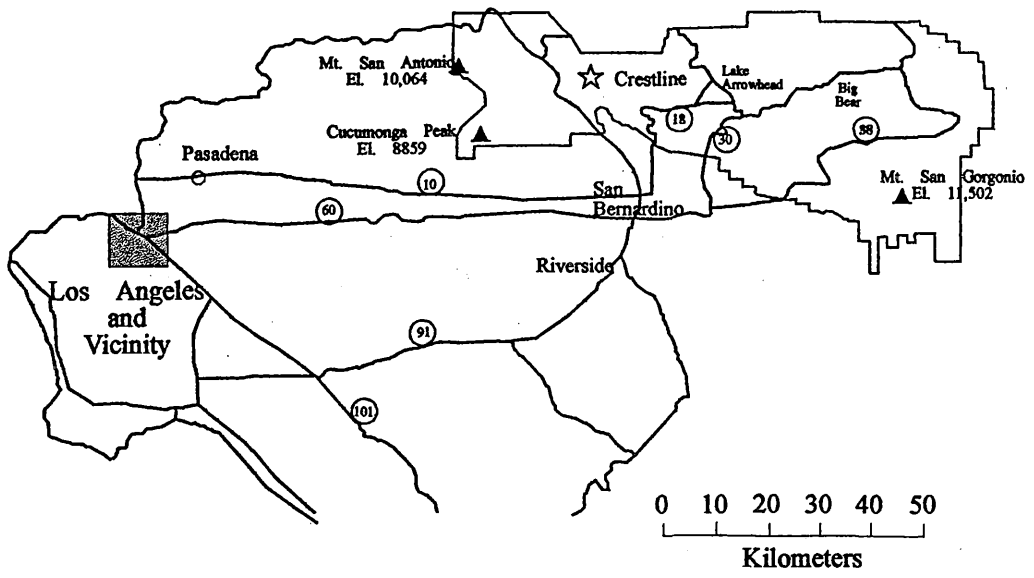
The measurement and analysis methods for rain, soil, throughfall, streamwater and foliar nutrients are described in detail in an appended manuscript by Fenn et al. The Valley of Mexico samples were mailed to Riverside for chemical analysis. Ozone injury to black cherry in the DDLL employed a standard methodology used for black cherry in the eastern United States and is described in the appended reprint (Skelly et al 1996). The method for measuring chronic ozone injury to Hartwegii pine in the DDLL was the same as that published by Miller et al. 1996 for ponderosa and Jeffrey pines in the western United States.

The project was carried out in three distinct phases involving cooperation between researchers from Pennsylvania State University, the Forest Service, Pacific Southwest Research Station and investigators led by Dra, Maria de Lourdes de Bauer at the Colegio de Postgraduados. First, the black cherry work completed by the Penn State group culminated in a publication (Skelly et al. 1996) (attached) which included Dionicio Alvarado as one of the cooperating scientists. The throughfall work involving Mark Fenn with Dra. de Bauer and associates has resulted in a report submitted for publication (see Fenn et al., attached manuscript). The third element involved the results of ozone and climate monitoring at DDLL and the San Bernardino Mountains at Barton Flats in southern California as well as measurement of chronic injury to the crowns of 50 Hartwegii pines at DDLL and similar numbers of ponderosa and Jeffrey pines at Camp Paivika and Barton Flats in the San Bernardino mountains. Paul Miller, David Jones and Susan Schilling provided training with the monitoring equipment for the DDLL and were responsible for climate and ozone monitoring and pine injury evaluations in California. The work in Mexico was completed under the supervision of Dra. De Bauer by Abel Quevado and Tomas Hernandez. These results have not been submitted for publication and are discussed below.

Results and Discussion

Ozone and Climate Monitoring

The principal climatic feature to be compared between the two sites (DDLL and the San Bernardino Mountains) are the wet (DDLL) and dry (SBM) summer climates as reflected in diurnal temperature, relative humidity and ozone measurements. The data presented here is for the July through December period of 1995. However the monitoring effort is still continuing at both locations. The following figures (Figures 2, 3, 4, 5, and 6) describe features of the summer and winter climates in relation to observed ozone concentrations.



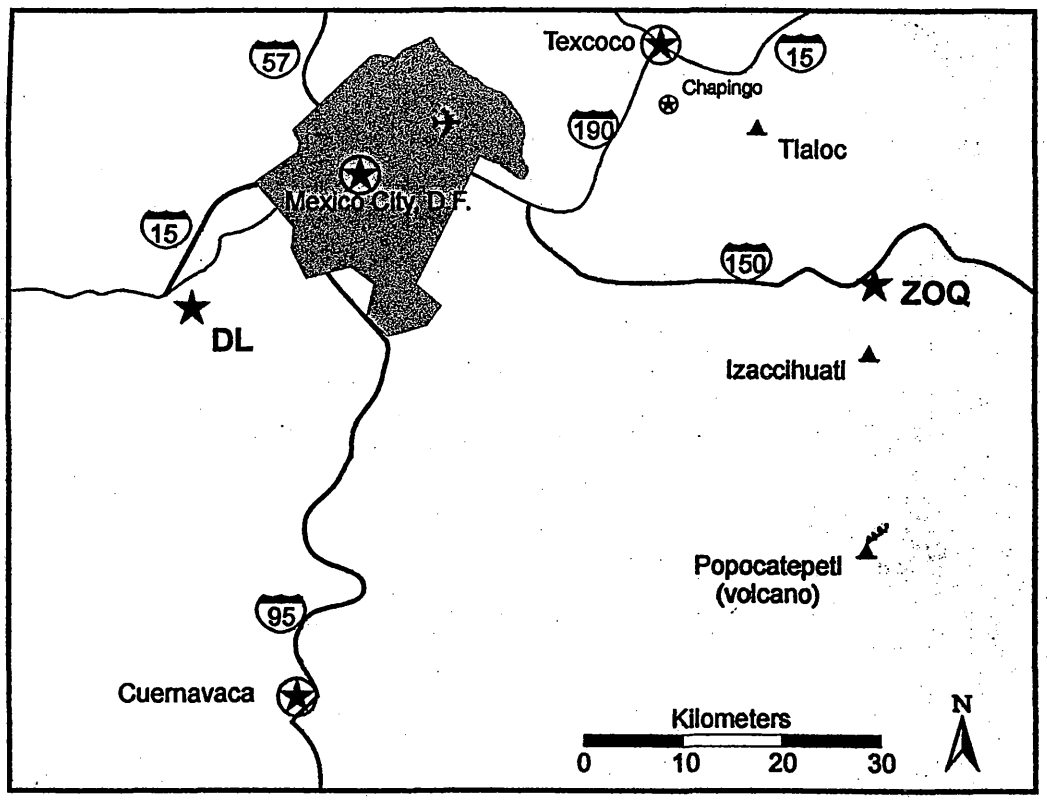


Figure 1. Maps showing the study areas in the San Bernardino Mountains east of Los Angeles (upper) and in the Valley of Mexico (lower) where climate and ozone were compared at Barton Flats and the Desierto De Los Leones, respectively, from July through December 1995. In the Valley of Mexico, throughfall and nutrient status were sampled at the Desierto De Los Leones (high air pollution) and ZOQ (a low air pollution site).

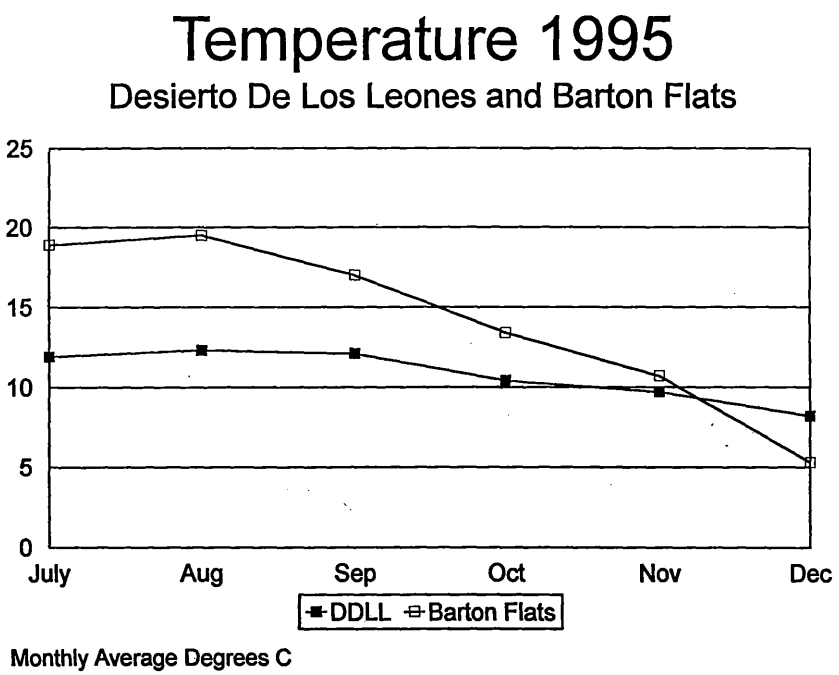


Figure 2. The monthly average temperature at Barton Flats from July to November was always warmer than at the Desierto De Los Leones while the December temperature at Barton Flats was cooler.

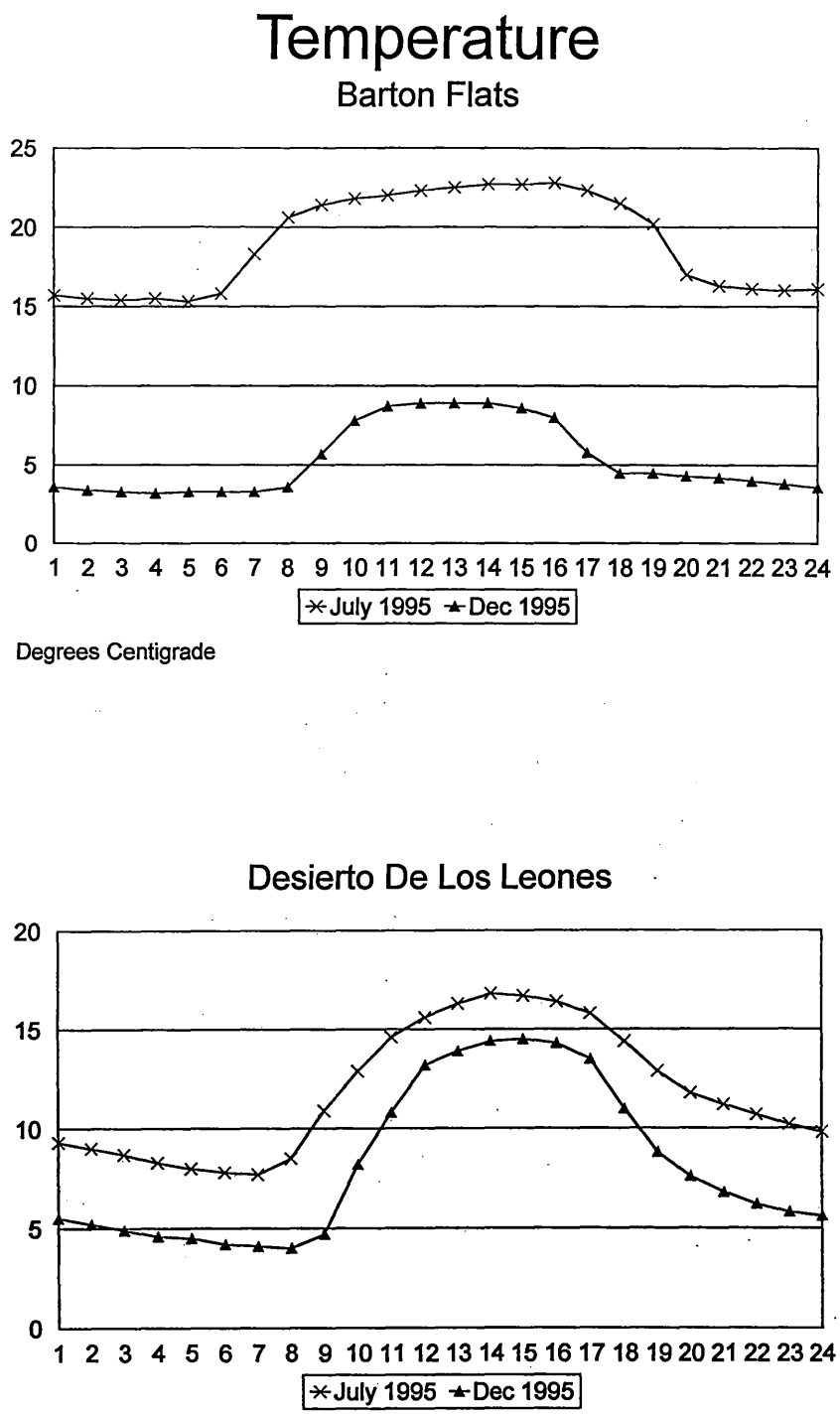
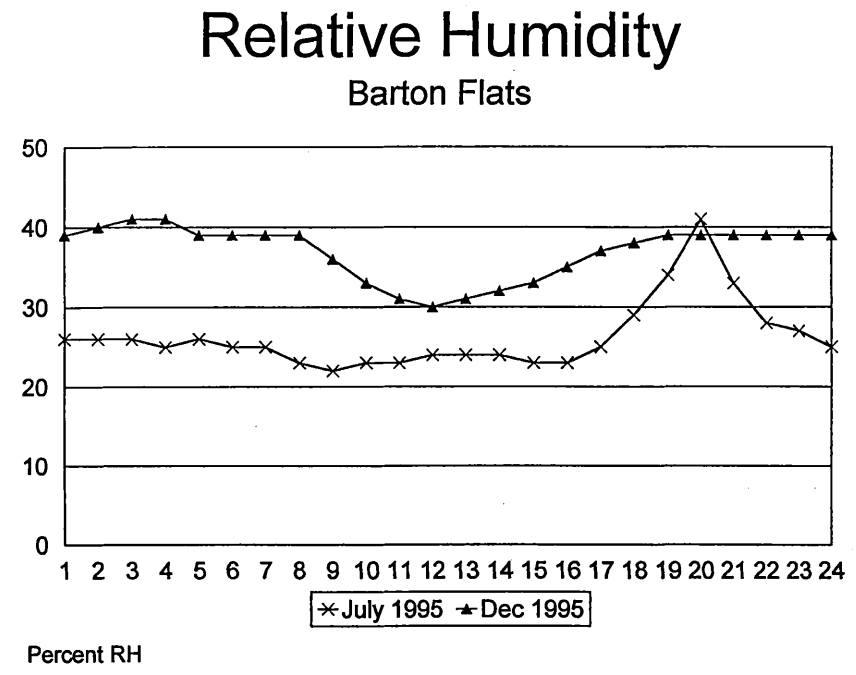


Figure 3. The diurnal curves for temperature at Barton Flats show a pronounced difference between July and December (upper) whereas the July and December curves for the Desierto De Los Leones were not widely divergent (lower).



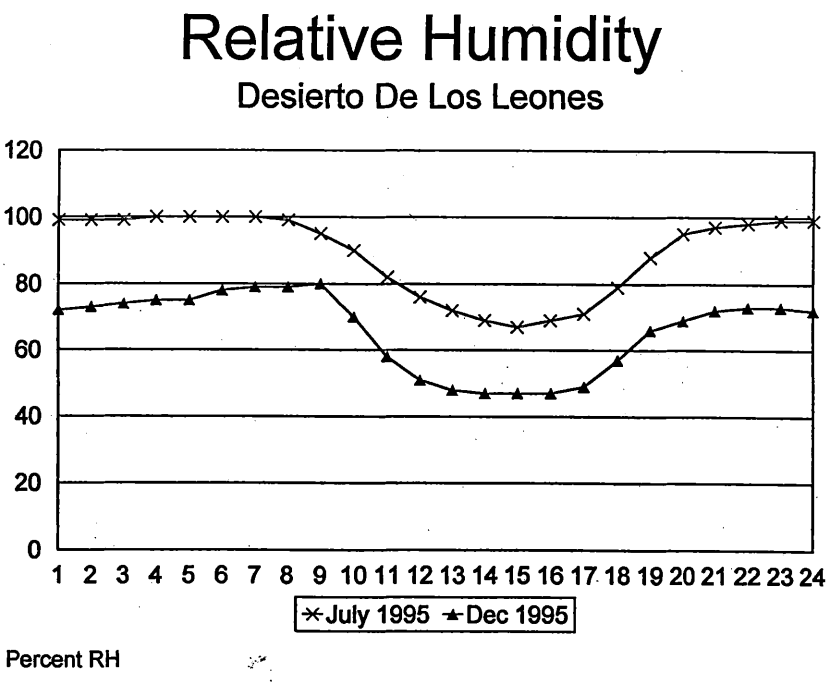


Figure 4. The diurnal curves for relative humidity at Barton Flats for July and December have different shapes (upper). The July peak at 2000 hrs is partially an indication of the arrival of moist marine air near the time of the evening ozone peak. The December relative humidity curve when the transport of ozone is minimal more closely resembles the shape of both the July and December curves at the Desierto De Los Leones (lower). The relative humidity is much higher at the Desierto De Los Leones than at Barton Flats in both July and December.

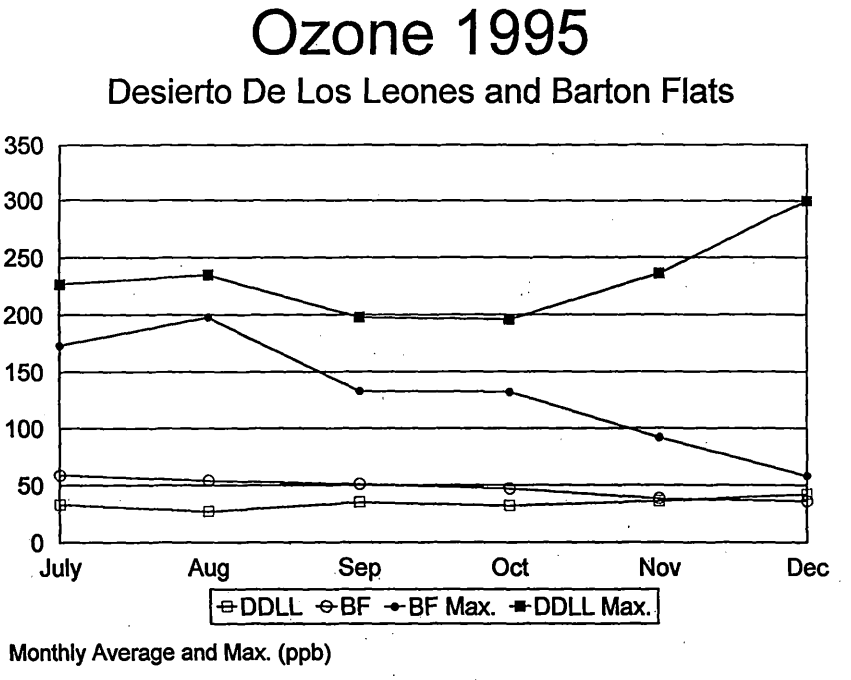
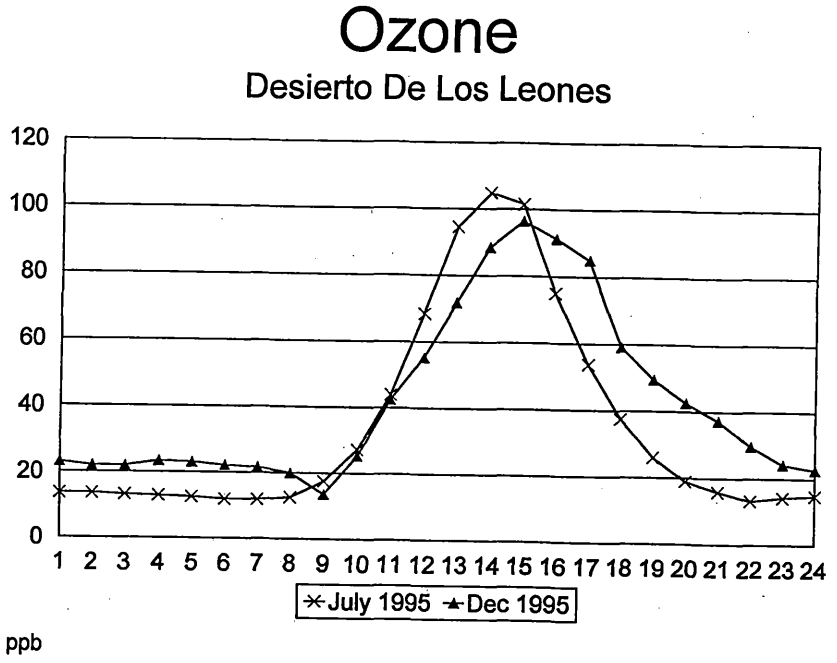


Figure 5. The monthly average ozone concentration at Barton Flats was higher than that at the Desierto De Los Leones from July to November, however, the December average was slightly higher at the Desierto De Los Leones in December. The maximum observed hourly ozone concentration for each month was always higher at the Desierto De Los Leones, especially in November and December.



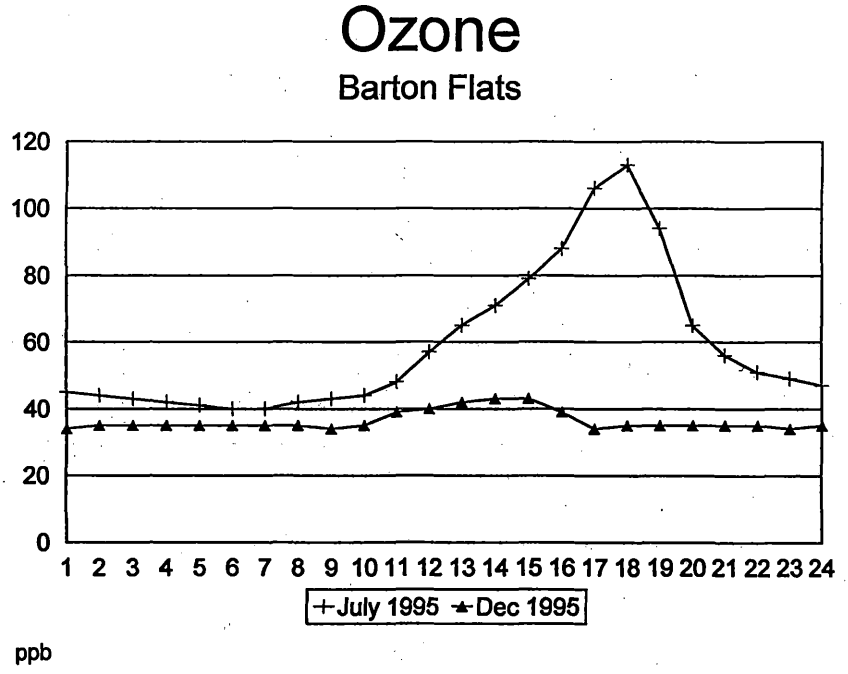
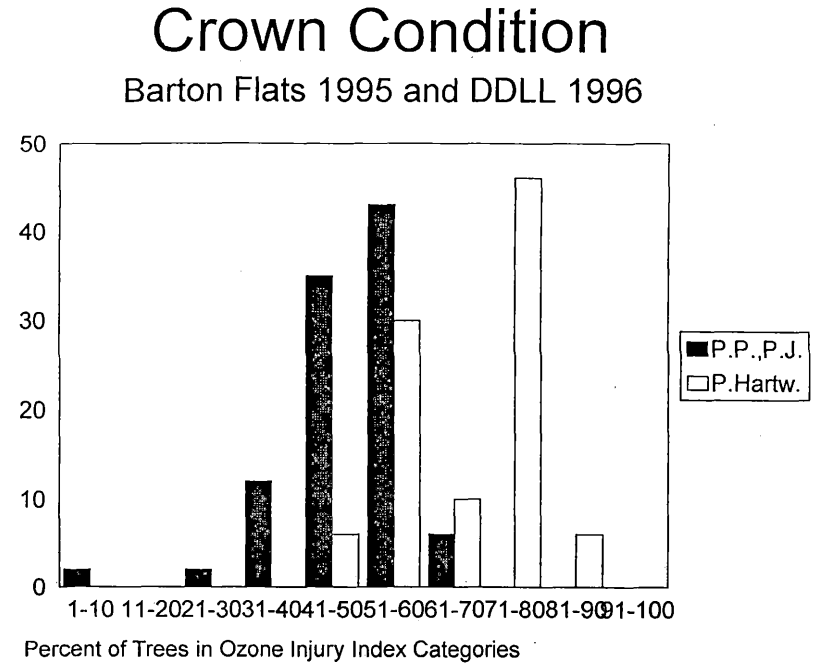


Figure 6. The diurnal curves for ozone are very similar in magnitude and only slightly different in timing of the daily peak in July and December at the Desierto De Los Leones (upper), however the transported ozone arrived later in the afternoon at Barton Flats than at the Desierto De Los Leones in July (a result of being further removed from the source area). There was no transported ozone peak at Barton Flats in December.

An earlier set of ozone data obtained from May 1990 to April 1991 at Crestline, CA (a South Coast Air Quality Management Station near Camp Paivika in the SBM) and the DDLL compared the 0600 to 2000 ozone average for a 1 year period (Miller, et al. 1994). Ozone concentrations during June through September were higher at Crestline. The weather is normally dry at Crestline during this period but is frequently rainy at DDLL. From October through the following April the average ozone concentration at DDLL was about the same or higher than Crestline when Crestline was in its rainy period and DDLL was dry. The data for monthly ozone values followed the same seasonal trend at the DDLL and Barton Flats for period reported here (Figure 5). The average monthly maximum ozone was higher than at Barton Flats during the entire period but particularly during November and December. The generally higher relative humidity at DDLL compared to Barton Flats may encourage greater stomatal conductance and thus higher ozone uptake. Warmer winter temperatures at DDLL would maintain a higher level of physiological activity which would also influence ozone uptake and it effects.

Comparisons of Ozone Injury to Pines

A standard procedure for evaluating ozone injury to pines allowed the condition of *Pinus hartwegii* at DDLL to be compared with a mixture of *P. Ponderosa* and *P. jeffreyi* at Barton Flats, the climate and air monitoring site in the eastern San Bernardino Mountains and with a site at Camp Paivika in the western part of the San Bernardinos where there is greater exposure to ozone. A population of 130 trees at Barton Flats was not as badly injured as the 50 trees at the DDLL (Figure 7, upper). The population of 50 trees at Camp Paivika had a nearly identical level of injury compared to the trees at DDLL (Figure 7, lower). The Camp Paivika site also has much more nitrogen deposition compared to Barton Flats. Although there is a high interest in the possible interaction of nitrogen and ozone, we are not prepared to speculate about the outcome based on the limited data available. On-going research in the SBM is addressing the ozone x nitrogen interaction.



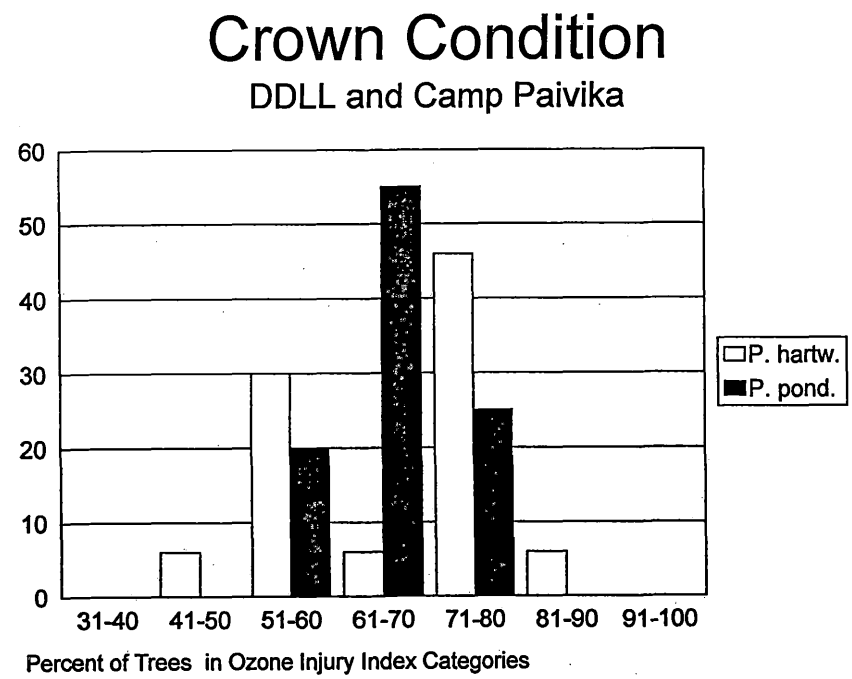


Figure 7. A standard method, the ozone injury index, was used to compare the crown condition of ponderosa (*Pinus ponderosa*) and Jeffrey (*Pinus jeffreyi*) pines at two sites in the San Bernardino Mountains with a sample of Hartwegii (*Pinus Hartwegii*) pines at the Desierto De Los Leones. The index ranges from 0 (no injury) to 100 (severe injury). At Barton Flats a sample of 130 ponderosa and Jeffrey pines is distributed in lower injury classes than the sample of 50 Hartwegii pines from the Desierto De Los Leones (upper), Barton Flats trees are considered to be only moderately damaged. When the same 50 tree sample of Hartwegii pines is compared with a 50 tree sample of ponderosa pines from the site in the San Bernardino mountains, Camp Paivika, with the highest amount of crown injury, the distribution in injury classes was about the same (lower).

The ozone injury index (OII) was designed specifically for use in describing pines in the western U.S. where normal retention of needle whorls is in the range of 1 to 8 whorls. *P. Hartwegii* ranges between 1 to 4 whorls (Hernandez, Personal Communication). During the computation of the OII the whorls older than 4 years are not included, for example, visible injury computations involve only the first four whorls. For this reason the OII computations for the Mexican pines was really not different from those for Californian pines, and this argues favorably for the comparability of the data from the different species.

Conclusions

- Improved Climate and Ozone Monitoring Station was Established at DDLL and Continues to Function.
- Climate, Ozone and Tree Injury Data was Obtained and Exchanged.
- Initial Comparisons Show Different Climatic and Ozone Pattens of Occurrence between The Valley of Mexico and southern California but Similar Levels of Ozone Injury to Pines. (See Figure 7, lower)
- The Foliage of Black Cherry *Prunus serotina* var. *capuli*, Proved to be an Excellent Bioindicator of Ozone Injury.
- Atmospheric Deposition of Nitrogen has Resulted in Nitrogen Saturation at the DDLL, However Its Severity and Extent in the Valley of Mexico is yet to be Determined.

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Appended Documents

(One reprint, one manuscript)

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OBSERVATIONS OF OZONE-INDUCED FOLIAR INJURY ON BLACK CHERRY (*PRUNUS SEROTINA*, VAR. *CAPULI*) WITHIN THE DESIERTO DE LOS LEONES NATIONAL PARK, MEXICO CITY

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Abstract

A survey for ozone-induced foliar injury of black cherry was conducted in mid-June 1995 within the Desierto de Los Leones National Park located southwest of Mexico City. Evaluations of the upper and lower tree crowns of 18 trees revealed evidence of significant upper surface stipple, leaf reddening and premature senescence on 72% of the trees. A general survey of an additional 169 trees disclosed that 41% exhibited similar symptoms. A gradient of increasing symptoms with increasing elevation was also evident. For the most part, asymptomatic trees were observed to be situated within well-shaded coves at the lower elevations with very few symptomatic trees present in these areas. © *1997 Elsevier Science Ltd. All rights reserved*

INTRODUCTION

The environment of the Mexico City area is highly conducive to the generation of photochemical oxidants, especially tropospheric ozone. Automobile traffic and urbanization as well as geographic, topographic and associated meteorological conditions all contribute to the conditions of pollutant buildup (Bravo, 1988). Recent reports demonstrate continuing significant air pollution problems within the Valley of Mexico (Bravo & Torres, 1995). Ambient ozone often exceeds the Mexican ozone air quality standard of 110 ppb for 1 h day^{-1} $year^{-1}$. During the period 1989 through to 1994, an average of 1250 instances of exceeding the standard were noted on an every year basis; peak 1 h averages often exceeded 200 ppb ozone with the high 1 h average of *ca* 430 ppb reported on 9 March 1992 (Bravo & Torres, 1995).

The vegetation within the urban and surrounding areas of the Mexico City airshed suffers from oxidant air pollutant stress; symptoms include premature chlorosis and leaf senescence, indicative of season-long oxidant exposures (Bauer & Krupa, 1990). Within Chapultepec Park of Mexico City many conifers (*Pinus* spp. and *Taxodium* spp.) have shown chlorosis, mottling and early needle senescence. Broadleaf species have shown varying degrees of upper surface stippling, leaf reddening and early leaf senescence, also indicative of ozone induced stress. Bauer and Krupa (1990), also surveyed vegetation to the southwest of Mexico City following the pattern of pollutant dispersion with predominant windflow patterns from the north and northeast; forested areas immediately downwind of the city were severely affected.

During the late summer and early fall of 1988, black cherry (*Prunus serotina*, var. *capuli*) within the urban green areas of Mexico City were observed to exhibit leaf chlorosis, adaxial stipple, general reddening and early leaf senescence. 'Capulin' trees are considered to be a subspecies of *P. serotina* (Rzedowski, 1978). Changing levels of symptom severity and sometimes necrosis with premature defoliations were all reported (Bauer & Chavez, 1991). These same symptoms were previously noted on *P. serotina* var. *capuli* trees to the southwest of the city in the Desierto de Los Leones National Park (DL), where severe ozone-induced foliar injuries have also been reported on sacred fir (*Abies religiosa* Schl.) (Alvarado *et al.*, 1993), *P. hartwegii*, Lindl. (Bauer *et al.*, 1985) and *P. montezumee*, Lamb. var. *lindleyi* (Hernandez & Bauer, 1984).

Black cherry (*P. serotina*, Ehrh.) has been identified in eastern United States as being very sensitive to tropospheric ozone air pollution (Davis & Skelly, 1992; Skelly *et al.*, 1992; Simini *et al.*, 1992). Symptoms are manifested as an upper leaf surface stipple which appears during the mid to late growing season in northcentral Pennsylvania. Older leaves are most severely affected with advancing symptoms of premature reddening and defoliation as the summer progresses; extremely sensitive individuals are completely defoliated by late August and/or early September.

Two prior visits by the senior author to the DL in June 1994 and March 1995 confirmed the presence of advanced and initial symptoms, respectively, that were typical of ozone-induced foliar injuries on black cherry under natural forest conditions. The study reported herein was initiated to more fully document the occurrence of ozone-induced, upper leaf stippling on black cherry (var. *capuli*) within the DL and to identify ozone-

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sensitive and tolerant individual black cherry for potential development as an *in-situ* native species bioindicator within the National Park.

MATERIALS AND METHODS

The study was conducted during the period 20–22 June 1995 within the DL at latitude 19°21′ and longitude 99° 15′ at an elevation of 2950–3500 m msl. The study was divided into two distinct efforts: (1) an intensive evaluation of mature canopy black cherry for foliar injuries and possible seed collection, in furthering the development of black cherry (var. *capuli*) as a bioindicator species within the DL; and (2) a general survey of larger numbers of black cherry within the DL in order to obtain estimates of numbers of sensitive black cherry (var. *capuli*) and estimations of the symptom severity for those individuals found to be ozone sensitive.

Intensive evaluation

The methods for intensive symptom evaluation of mature canopy trees reported by Skelly *et al.* (1995) and Hildebrand *et al.* (1996) were employed for the evaluation of trees at various locations within the DL. All selected trees were mapped for possible further evaluations. Large mature canopy trees were chosen for sampling based upon the presence or absence of notable symptoms and the presence of mature seed via ground observations. When possible, trees were sampled with pole pruners but taller individuals were climbed with ropes for access to the upper crown branches. Three branches each were sampled from the upper outer crown and the lower sun-exposed side branches of each tree. On each branchlet, approximately 30 leaves were evaluated for the presence of typical adaxial stipple and reddening. Percent leaves showing symptoms was estimated into 5% classes and the presence of adaxial stipple and general leaf reddening was estimated using the Horsfall–Barratt index as developed for such purposes (Nash *et al.*, 1992).

General survey

A walking survey was conducted along the main road beginning at the DL entrance pavilion at the southeast end and proceeding toward the Monastery and main entrance of the DL to the northwest. Black cherry within 16 m (50ft) of either side of the road and of diameter breast height (DBH; 1.4 m) of >5 cm (diameter tape) were evaluated for the presence or absence of upper surface stipple and leaf reddening. Observations were made on intact lower crown branches of many trees. Top branches were evaluated for symptoms using binoculars but when leaves on larger crowns were not readily visible, trees were climbed for collection of upper crown branchlets. Since many trees were below the road and situated on steep slopes, visual inspection of the top of their crowns was often possible from the side and/or from above. Trees were simply recorded as asymptomatic or symptomatic with notations made for evidence of symptoms within upper and lower crown leaves.

RESULTS

Intensive evaluation

During the 20–22 June sampling period crowns of a total of 18 mature canopy trees were intensively evaluated for foliar injuries as induced by ambient ozone exposures. Trees were not sampled at random, but rather were selected for the dual purposes of evaluating symptom severity and seed collection. Hence trees were selected that showed varying degrees of symptoms along with ripening seed. The numbers of asymptomatic and symptomatic black cherry and the severity of symptoms found within the sensitive trees sampled are presented in Table 1. Of the 18 trees evaluated, six showed symptoms in the top and bottom crown branches while seven exhibited symptoms only within the lower crown; five apparently asymptomatic trees were selected and subsequently proved to be free of symptoms following branchlet sampling for closer observations.

On trees with foliar symptoms expressed on both the upper and lower crown branches, leaves within the lower crowns proved to be more symptomatic, with average scores for percent leaves and percent leaf area affected of 42 and 7% and 83 and 25% for the top and lower crown branchlets, respectively. On these same six trees, with only two exceptions in the upper crown of two trees, all three branchlets sampled within the upper and lower crowns of symptomatic trees exhibited ozone-injured leaves. For trees with symptomatic leaves found only in the lower branchlets, percent leaves affected and percent leaf area symptomatic were 68 and 23%, respectively; leaves on top branches displayed no obvious ozone-induced symptoms. During this portion of the survey it became obvious that there were more symptomatic trees at the higher elevation of the DL with more intense symptoms evident on trees within and above 'Cemetery Curve' (3000 m msl) a well known area of the DL for intensive symptoms on pines and fir (Alvarado *et al.*, 1993; Hernandez & Bauer, 1984).

Table 1. Incidence and severity of ozone-induced foliar injury on symptomatic black cherry sampled within the intensive survey conducted 20–22 June 1995, Desierto de Los Leones National Park

		% Leaves and % leaf area			
		Upper crown		Lower crown	
Crown position	No. of trees	L	LA	L	LA
Top and bottom	6	42 (±7)	7 (±3)83	83 (±5)	25 (±5)
Bottom only	7	—	—	68 (±7)	23 (±4)
Top only	0	0	0	—	—

Data presented as percent leaves (L) and percent leaf area (LA) affected (standard error) on symptomatic leaves over three upper crown and three lower crown branchlets, 30 leaves per branchlets.

General survey

A total of 169 black cherry were evaluated for foliar ozone injury along a *ca* 3.5 km section of the main DL road. It is not possible to conclude that the 169 observed trees constituted a 100% survey of all trees in existence within 16 m of either side of the road but none was intentionally omitted during the survey. All trees > 5 cm at DBH were examined; many clumps of black cherry derived from stumps were included but only the largest diameter tree within each clump was evaluated. Of the 169 trees observed, 69 (41%) were found to be sensitive while 100 (59%) appeared as tolerant of ambient ozone exposures (Table 2). The tolerant trees were dramatically devoid of ozone-induced symptoms and most were noted as very vigorous with robust, full crowns and dark green leaves. Although not measured, terminal growth on these tolerant individuals was noted to be excellent.

Of the 69 symptomatic trees, 27 (40%) had symptoms on the top and bottom crown leaves while 42 (60%) had symptoms only on the lower crown leaves; no trees were found with symptoms only on the top-most leaves. The distribution of symptomatic and non-symptomatic trees also followed an elevational gradient with 'Cemetery Curve' serving as a convenient point to describe observed differences (Table 3). Of 52 trees found above the curve (3000–3500 m msl), 31 (60%) were noted as symptomatic with many showing advanced symptoms and defoliation, while of 117 trees below (3000–2950 m msl) only 38 (32%) were found symptomatic with many showing only slight stippling of the lower leaves; chi-square tests showed elevational differences in symptom incidence to be significant. Numerous trees were found in well-protected and shaded coves along the Park road and these were lush green with excellent form and growth.

DISCUSSION

The Desierto de Los Leones National Park is situated within the Mexico City airshed and routinely receives high ozone concentrations on a daily basis. Unfortunately, no continuous ozone data were available for the months prior to the black cherry survey in 1995. However, sporadically recorded data in the spring of 1995 did show frequent ozone concentrations in excess of 200 ppb O_3 with a reading of 254 ppb O_3 being recorded on 25 March 1995 (T. Hernandez, personal communication). Ozone exposures have previously been reported as consistently high with midday hourly averages (May–October) approaching 90 ppb O_3. Seven exceedences of > 250 ppb were recorded during the period May 1990–April 1991 (Miller *et al.*, 1994). It is highly probable that ozone exposures were present within the DL prior to the study and throughout the 1995 growing season.

Typical upper surface stipple indicative of ozone exposures was observed on numerous black cherry (*P. serotina* var. *carpuli*) growing naturally within the DL. Within the intensive survey, the symptoms were considered to be identical to symptoms observed on black cherry (*P. serotina*) in response to ambient ozone exposures in forests of northcentral Pennsylvania (Simini *et al.*, 1992) and within the Shenandoah National Park, VA (Hildebrand *et al.*, 1996). The percent of trees showing symptoms was considerably lower within the DL as compared to observations in Pennsylvania and the Shenandoah, where 65 and 67% of trees surveyed were found symptomatic, respectively (Davis & Bennett, 1986; Hildebrand *et al.*, 1996). However, symptom severity was much greater on trees within the DL (average high of 25% leaf area affected) as compared to the black cherry within the Shenandoah (average high of 8% leaf area affected) (Hildebrand *et al.*, 1996).

Within the general survey, the finding of increasing foliar injury due to increasing ozone exposures with increasing elevation is similar to the findings of Winner *et al.* (1989) and Gilliam *et al.* (1989) in the Shenandoah. A rapid increase in elevation is notable beyond 'Cemetery Curve' within the DL, as well as a change in exposure along the road used in the survey from northeast to west and southwest exposures.

The foliar symptoms observed on black cherry within the DL are considered to be quite severe and of concern to the continuing health and productivity for this species at the higher elevations of the DL. Defoliations of 80% and greater were quite common with no evidence of causes other than symptom responses typical of ozone exposures. A very large group of asymptomatic trees was observed within coves and areas that were almost

Table 2. Number of asymptomatic and symptomatic trees and crown position of observed symptoms during a survey of trees > 5.0 cm DBH and within 16.5 m of the main road within the Desierto de Los Leones National Park, 21 June 1995

		Crown position for symptoms		
Symptoms	No. of trees	Top only	Bottom only	Top and bottom
Asymptomatic	100 (59%)	—	—	—
Symptomatic	69 (41%)	0	42 (60%)	27 (40%)

Table 3. Tree location, symptoms and crown position of symptoms for black cherry found during a survey of trees > 5.0 cm DBH and within 16.5 m of the main road traversing the Desierto de Los Leones National Park, 21 June 1995

			Crown position for symptoms		
Position in park	No. of trees	No. of trees symptomatic	Top only	Bottom only	Top and bottom
Below 'Cemetery Curve'	117 (70%)	38 (32%)*	0	21 (55%)	17 (45%)
Above 'Cemetery Curve'	52 (30%)	31 (60%)	0	21 (68%)	10 (32%)

*Significantly different at $\alpha = 0.01$, χ^2 test at 10.97 with df = 1.

completely shaded at the lower elevations. Obviously. there is a need for continuous monitoring of ambient ozone concentrations within the DL with preference for several monitors to be positioned at various elevations to gain more information on exposure/response relationships.

Seeds were collected from 18 trees within the intensive survey. Seedlings derived from these seed sources will be fumigated under controlled conditions to confirm sensitivities and their potential use as bioindicators of ozone *in situ* within the DL.

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Nitrogen and Sulfur Deposition and Forest Nutrient Status in the Valley of Mexico

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Nitrogen and Sulfur Deposition and Forest Nutrient Status in the Valley of Mexico

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Abstract. Mexico City experiences some of the most severe air pollution in the world. Ozone injury has been documented in sensitive tree species in urban and forested areas in the Valley of Mexico. However, little is known of the levels of other atmospheric pollutants and their ecological effects on forests in the Valley of Mexico. In this study we measured bulk throughfall deposition of inorganic nitrogen (N) and sulfur (S) for one year at a forested site upwind (east) and downwind (southwest) of Mexico City. We also measured edaphic and plant indicators of N and S nutrient status. Preliminary streamwater sampling and analysis for NO_3^- and SO_4^{2-} concentrations was also determined as an indicator of watershed-level N and S loss. Annual bulk throughfall deposition of inorganic N and S at the high-pollution forested site 23 km southwest of Mexico City (Desierto de los Leones National Park; DL) was 18.9 and 20.4 kg ha^{-1}. Similar values at Zoquiapan (ZOQ) a relatively low-pollution site 53 km east of Mexico City were 5.5 and 8.8 kg ha^{-1} yr^{-1}. Foliar concentrations of N, foliar N:P and C:N ratios, soil C:N ratios, and streamwater NO_3^- concentrations indicate that the forest at DL is N enriched, presumably as a result of chronic N deposition. Sulfur concentrations in current-year foliage were also slightly greater at DL than at ZOQ, but S concentrations in one-year-old foliage were not statistically different among the two sites. Streamwater concentrations of NO_3^- ranged from 0.8 to 44.6 μEq L^{-1} at DL compared to 0.0 to 11.3 μEq L^{-1} at ZOQ. In summary, these findings support the hypothesis that elevated N deposition at DL has increased N fertility and resulted in export of excess N as NO_3^- in streamwater.

Introduction

Mexico City suffers from severe photochemical smog problems, especially during the dry winter season (Miller *et al.*, 1994). Ozone injury has been documented in a number of plants in urban, rural and montane areas in the Valley of Mexico (Bauer and Hernández-Tejeda, 1986). Severe forest decline has been described in some areas of the Desierto de los Leones National Park (DL) located ca. 23 km southwest of Mexico City. Air pollution has been implicated as a possible factor in the decline (Alvarado *et al.*, 1993; Bauer *et al.*, 1985; Bauer and Krupa, 1990). Air pollution concentrations are elevated in DL because of proximity to the large urban pollution source area and the prevailing northeasterly winds from Mexico City (Bauer, 1991)

Based on published emission inventories for metropolitan Mexico City (Bravo, 1988), elevated deposition of nitrogen (N) and sulfur (S) pollutants is also expected to occur in forests downwind of Mexico City. Fossil fuel consumption, mainly for transportation is the primary source of atmospheric N pollutants in Mexico City. Sulfurous air pollutants come primarily from burning of fossil fuels with high S content (Velasco, 1983). However, few studies have quantified N and S deposition and the potential effects of these pollutants on forests within the Valley of Mexico (Baez *et al.*, 1997b).

Many studies have demonstrated a close relationship between levels of N deposition and effects on chemical processes in soil such as soil acidification, stimulation of nitrification and nitrate leaching, leaching of counterbalancing cations, and alleviation of N deficiency (Fenn *et al.*, 1997). The objectives of this study were to compare N and S deposition and indicators of nutrient status in a forest located downwind (southwest) of Mexico City and another forest upwind (east) of Mexico City. We hypothesized that elevated N and S deposition occurs in forests downwind of Mexico City and that

signals of chronic N and S deposition to these forests would be observable as higher N and S concentrations in soil and vegetation, and as increased losses of nitrate in streamwater.

Methods

Research sites

Zoquiapan Experimental Forest (low deposition) and the Desierto de los Leones National Park and Recreation Area (high deposition) are the two forested sites selected for this study. Our study site in the southwestern portion of the Desierto de los Leones National Park (DL) is located 23 km southwest of Mexico City in the direction of the prevailing winds from Mexico City. This area is known to be highly polluted as a result of the polluted air transported to the site from Mexico City. The Zoquiapan Experimental Forest (ZOQ) is located in the southeast corner of Zoquiapan National Park, 53 km east of Mexico City (Figure 1). Descriptive characteristics of these sites are given in Table I. Precipitation in the Valley of Mexico occurs predominantly from May through September. Precipitation at the study sites occurs as rainfall or hail. Snowfall rarely occurs except at sites above 4000 m in elevation. The dominant tree species at both sites are Pinus hartwegii Lindl. and Abies religiosa Schl (Rzedowski, 1978). There are frequent local fires in the forest in the Zoquiapan area.

Throughfall collection and dry deposition fluxes

Bulk throughfall was collected at both sites from March 1996 to March 1997. Throughfall was collected in standard collectors consisting of a funnel (13 cm diameter) connected to opaque collection bottles. The collection surface area was 132.7 cm^2. Throughfall was collected on a weekly basis during the wet season (March through October, and on an event basis thereafter. Throughfall collectors were

placed in four parallel transects at each site with eight collectors per transect, for a total of 32 collectors per site. Throughfall volumes were recorded in the field and a subsample was collected and maintained under refrigeration (approx. 4°). Phenyl mercury acetate was added to the subsamples (10 mg mercury L^{-1}) as a preservative and the samples were shipped to the Forest Fire Laboratory in Riverside, California, USA for chemical analysis. Ammonium (NH_4^+), nitrate (NO_3^-), and sulfate (SO_4^{2-}) concentrations were determined in the throughfall samples using liquid ion chromatography (Dionex[1] series 4000i, Sunnyvale, CA).

Dry deposition fluxes of NO_3^-, NH_4^+ and SO_4^{2-} to surrogate surfaces were also determined during the winter dry season in 1994 at DL and ZOQ. At ZOQ, dry deposition collectors were located near the hill named El Papayo, which is in the northwest corner of the Zoquiapan Experimental Forest, approximately 4 km northwest of the throughfall study site (Figure 1). Paper filter disks (Whatman no. 41, 47 mm diameter) were used as collection surfaces for comparing dry deposition fluxes at DL and ZOQ as described previously (Fenn and Bytnerowicz, 1993). Filter disks were exposed for two weeks after which the disks were collected and new disks installed. The five exposure periods began on Feb. 4, 1994 and ended on April 15, 1994. The exposed filter disks were extracted with deionized and distilled water and ionic concentrations determined with ion chromatography.

Indicators of Forest Nutrient Status

Various soil, plant, and hydrologic nutrient status indicators were measured at the two sites in order to

[1]Mention of trade names or products is for information only and does not imply endorsement by the U.S. Department of Agriculture.

see if elevated atmospheric deposition of N and S was reflected in nutrient concentrations of plants, soil and streamwater.

Soil indicators

Soils were collected at both sites in March and December 1996. Seven soil samples were collected from the top 15 cm and from the 15-30 cm depth in seven pits located along the same transects where throughfall was collected. Concentrations of NO_3^-, NH_4^+, and SO_4^{2-} in water extracts of soil were determined by adding 15 ml of deionized-distilled water to 7.5 g of soil and extracting on a wrist action shaker for 1 hr. After centrifuging for 15 minutes, ionic concentrations were determined in the supernatant. Total N, C and S were also determined in the soil from both depths with a combustion analyzer (Carlo Erba Instruments, Milan, Italy; Model NA 1500, Series 2). Soil pH was determined on a 1:2 mixture of soil and 0.01 M $CaCl_2$ (Fenn *et al.*, 1996).

Foliar indicators

Current-year and one-year old foliage were collected from twelve trees at DL and ZOQ in December 1996. Four branches were collected from each tree and the four annual whorls of each age class were composited to obtain one sample per age class from each tree. Foliage was analyzed for total C, N, and S by combustion analysis as described above. Total P in foliage was determined from nitric-perchloric digestion and analysis with a Technicon TRAACS 800 autoanalyzer (Glaubig and Poth, 1993).

Streamwater chemistry

A preliminary streamwater survey was performed in order to see if the general pattern of streamwater NO_3^- and SO_4^{2-} export paralleled atmospheric deposition inputs at DL and ZOQ. Several streams were sampled within the watershed at DL and ZOQ from December 1996 until March 1997. Three samples were taken from each stream by rinsing the collection bottle three times with streamwater and filling the bottle with streamwater. The samples were then transported to the laboratory in the Colegio de Postgraduados and frozen. Within a few days the samples were shipped to the Riverside Forest Fire Laboratory and stored in a freezer until analyzed for NO_3^-, NH_4^+, and SO_4^{2-} via liquid ion chromatography as described previously (Fenn *et al.*, 1996). Since NH_4^+ was not detected in any of the early streamwater samples, later collections were not analyzed for NH_4^+.

Statistical analyses

Data analysis was performed using SigmaStat™ statistical software from Jandel Scientific Software (Fox *et al.*, 1994). Differences in ion concentrations in throughfall and nutrient concentrations in foliage and soil between DL and ZOQ were determined by t-tests. Comparisons of dry deposition fluxes to surrogate surfaces were tested using one-way repeated measures ANOVA on ranks, followed by Dunnett's test for mean comparison. Differences were considered statistically significant at $p \leq 0.10$ (Fox *et al.*, 1994).

Results

Throughfall and dry deposition

Annual inorganic N (NH_4-N + NO_3-N) and S deposition at DL were 18.5 and 20.4 kg ha^{-1}. Analogous values at ZOQ were 5.5 and 8.8 kg ha^{-1} yr^{-1} (Figure 2). Annual throughfall was 146 cm at DL and 78 cm at ZOQ. Patterns of cumulative deposition inputs of NO_3^- and NH_4^+ paralleled cumulative precipitation volume at DL, but at ZOQ lines plotting cumulative deposition of NO_3^- and NH_4^+ were less responsive, lagging behind the trend of cumulative precipitation. Cumulative SO_4^{2-} deposition trends closely tracked cumulative precipitation at both sites (Figure 2). Volume-weighted annual mean concentrations of NH_4^+ and NO_3^- in throughfall were 1.6 and 1.8 times higher at DL than at ZOQ, while SO_4^{2-} concentrations in throughfall were only 1.2 times higher at DL (Figure 3).

Deposition fluxes of NO_3^- and SO_4^{2-} to surrogate surfaces were significantly greater at DL compared to the Papayo site in ZOQ (Figure 4). Fluxes of NH_4^+ to the paper filter disks were not significantly different between the two sites, however.

Soil indicators

Ionic concentrations in soil tended to be higher in March before the rainy season began compared to samples collected in December, three months after the wet season. Sulfate concentrations in soil extracts were low (4.5 to 8.6 mg kg^{-1}) and varied little between sites, sampling depths, and date (Figure 5). Ammonium concentrations in soil extracts ranged from 0.0 to 1.2 mg kg^{-1}, and were significantly greater at DL in March but not in December. No NH_4^+ was detected in aqueous soil extracts of the December 15-30 cm depth samples. The nitrate:sulfate concentration ratio in water extracts was typically 2-3 times higher in March than in December. Nitrate concentrations were

consistently higher at DL than at ZOQ (Figure 5).

Total soil C and N was significantly higher at DL in all cases. Total soil S tended to be higher at DL as well, but differences in S content were significant only in the December samples from the 0-15 cm depth ($p=0.15$ for the 15-30 cm depth in December). C:N ratios were not significantly different between DL and ZOQ (Table II). Average values for soil pH showed a tendency towards greater soil acidity at DL, but differences between DL and ZOQ were not statistically significant. However, the p value was 0.13 for comparison of soil pH at the 15-30 cm depth at the two sites in March 1996 (Table II).

Foliar indicators

Total N concentrations and N:P ratios in 1995 and 1996 foliage were higher at DL than at ZOQ, but total P concentrations did not differ among the two sites. Total S concentrations in 1995 foliage were similar at DL and ZOQ, but S in 1996 foliage was slightly higher at DL (Figure 6). Foliar N:S ratios were higher at DL in 1995 needles, but N:S ratios for 1996 needles didn't differ between the two sites. Foliar C:N was lower at DL for both years (Figure 6).

Streamwater chemistry

Except for two data points, SO_4^{2-} concentrations in streamwater were clearly higher at ZOQ than at DL. Ignoring the two possible outlier points, SO_4^{2-} concentrations in streamwater at ZOQ ranged from 130 to 226 μEq L^{-1}, compared to 28 to 92 μEq L^{-1} at DL (Figure 7). Differences in NO_3^- concentrations in streamwater between the two sites was less dramatic than for SO_4^{2-}. Nonetheless,

NO_3^- concentrations were often much higher at DL, where values ranged from (1-45 μEq L^{-1}) compared to 0-11 μEq L^{-1} at ZOQ (Figure 7). Nitrate concentrations in 50% of the streamwater samples from DL were $\geq$ 15 μEq L^{-1}, while at ZOQ, 75% of the streamwater samples contained < 10 μEq L^{-1} NO_3^-.

Discussion

Nitrogen and sulfur deposition

Bulk throughfall deposition of N and S at DL was relatively high compared to many forests throughout the world. This finding was not unexpected considering the high emissions of N and S oxides from Mexico City (Bravo, 1988; Velasco, 1983). Los Angeles, California (USA) and Mexico City are widely known to experience high photochemical smog exposure because of meteorological and topographical features that in combination with elevated emissions of N oxides and hydrocarbons from fossil fuel burning favor photochemical reactions and the buildup of high pollutant concentrations (Miller *et al.*, 1994). However, S emissions in the Los Angeles Air Basin are less than ten percent as high as N emissions (South Coast Air Quality Management District, 1994). Sulfur deposition levels in a high-pollution site in the San Bernardino Mountains east of Los Angeles were ca. six to seven times lower than S deposition at DL (Fenn and Bytnerowicz, 1993). However, forests in the Los Angeles Air Basin, which are close to the ocean (i.e., within 80 km) can experience elevated S deposition as a result of seasalt sources of S (Fenn and Kiefer, 1998). Sulfur deposition in the Valley of Mexico is relatively high due to industrial sources and burning of fuels with a high S content (Velasco, 1983).

In our study, ionic concentrations in throughfall decreased as follows: $SO_4^{2-} > NO_3^- > NH_4^+$. In two recent studies of wet deposition in the Valley of Mexico (on the northern flank of the volcano Popocatépetl 70 km SE of Mexico City, and Rancho Viejo, a forested site 80 km SW of Mexico City) ion concentrations decreased in the following order: $SO_4^{2-} > NH_4^+ > NO_3^-$ (Baez *et al.*, 1997a; 1997b). These sites are further from Mexico City than DL (23 km SW of Mexico City) and ZOQ (53 km E of Mexico City) and are less affected by air pollution from Mexico City. Ion concentration data from the studies of Baez *et al.* (1997a; 1997b) are not directly comparable to our data because they collected precipitation or Coldwater, but did not collect throughfall. Baez *et al.* (1997a) concluded that Mexico City air pollution did not affect cloud or rain water chemistry at Popocatépetl, but that wet deposition was affected by pollution from the city of Puebla or from volcanic emissions--depending on wind direction during precipitation or cloud events.

Sulfur deposition in throughfall is generally considered to be a reasonable estimate of total S deposition to a forest. However, many studies demonstrate that 20 to 40% of atmospheric N deposited to a forest is retained within the canopy and thus not measured in throughfall analysis (Cadle *et al.*, 1991; Friedland *et al.*, 1991; Hanson and Garten, 1992; Lovett, 1992; Lovett and Lindberg, 1993; Marshall and Cadle, 1989; Schulze, 1989). Assuming that significant canopy retention of N also occurred in this study, total N deposition to the forest expressed on a mass basis (kg ha^{-1}) was slightly higher than total S deposition. For example, if the forest canopy retained from 20-40% of atmospherically-deposited N, total N deposition would be 22.7 to 26.5 kg ha^{-1} yr^{-1} at DL and 6.6 to 7.7 kg ha^{-1} yr^{-1} at ZOQ. In any case, deposition of N and S to the forest at DL is 10 to 20 times greater than levels measured in forests with minimal anthropogenic atmospheric deposition, assuming that background levels of N and S deposition in relatively pristine forests is ca. 1-2 kg ha^{-1} yr^{-1} (Young *et al.*, 1988). Deposition of N and S at ZOQ was approximately 3 to 9 times greater than background levels.

Concentrations of NO_3^- and NH_4^+ in throughfall at DL were 1.8 and 1.6 times greater than at ZOQ, while SO_4^{2-} concentrations were only 1.2 times greater at DL. The lower DL:ZOQ concentration ratio for S compared to N, suggests that there are sources of atmospheric S other than air pollution from Mexico City which contribute to S loading at ZOQ. Dry deposition fluxes of SO_4^{2-} to the surrogate surfaces at DL and ZOQ were highly similar on some dates, which also supports the hypothesis that there are significant atmospheric sources of S pollution in forests at ZOQ. Possible additional sources of S include local industrial sources or volcanic S emissions. The volcano Popocatépetl, located 28 km south/southeast from ZOQ, has increased in activity since 1991 and may be a source of SO_2 at ZOQ. Increased wet deposition of SO_4^{2-}, NO_3^-, and possibly other ions has been observed downwind of Popocatépetl (Baez *et al.*, 1997a)

Greater total annual N and S deposition at DL may have been partially due to the greater volume of throughfall collected at DL (Prado-Fiedler, 1990). However, because volume-weighted ionic concentrations in throughfall were also higher at DL, this indicates that greater atmospheric concentrations was the main factor leading to greater total N and S deposition at DL compared to ZOQ. Greater dry deposition fluxes of NO_3^- and SO_4^{2-} to surrogate surface collectors at DL compared to ZOQ (Papayo) also support this conclusion.

Forest nutrient status

Plant, soil and hydrologic indicators suggest that atmospheric deposition of N has increased N availability in soil, N concentrations in foliage, and NO_3^- losses in streamwater. The effects of S deposition on S availability and plant S concentrations were not as strong as for N. In fact, SO_4^{2-} concentrations in streamwater were consistently higher at ZOQ than at DL. This is probably more a

result of inherent soil SO_4^{2-} storage and release, and leaching that would occur even in the absence of elevated atmospheric deposition.

Possibly the strongest indicator of enhanced N fertility at DL is the higher foliar N:P ratio and lower foliar C:N ratio at DL compared to ZOQ. Nitrate and ammonium concentrations in soil also indicate greater N availability at DL, probably as a result of more nutrient-rich soil organic matter and higher nitrification rates. A particularly strong indicator of N enrichment of the forest is demonstrated by streamwater NO_3^- concentrations. While only three months of preliminary streamwater data were collected, the trends clearly indicate that NO_3^- export in streamwater is significantly greater in the DL area than in the ZOQ area. However, seasonal trends in streamwater NO_3^- concentrations from throughout the year are needed to more fully characterize watershed N retention and loss patterns. Seasonal trends and patterns of NO_3^- export indicate the degree of watershed N saturation according to the conceptual watershed N saturation model (Stoddard, 1994). The Stoddard watershed N saturation model, and the analogous terrestrial N saturation model (Aber *et al.*, 1989) describe four progressive stages of development in regards to N saturation. The data presented in this paper suggests that the forest at DL is at least at stage 1 and probably progressing toward stage 2 of the terrestrial conceptual model. Nitrogen fertilization studies would be helpful in determining whether N limitation of tree growth at DL has been reversed as a result of chronic N deposition. The watersheds at DL are exporting high NO_3^- concentrations. Twelve of 24 stream samples contained NO_3^- concentrations $\geq$ 15 μEq L^{-1}), concentrations which are typically found in watersheds at or approaching stage 2 of the Stoddard model (Stoddard, 1994). However, streamwater data during the summer growing season is needed to confirm this hypothesis. The primary definition of stage 2 watershed N saturation is when the terrestrial watershed and streams are incapable of retaining excess N even when biotic N demand is greatest during the warmer months.

Conclusions

Both N and S deposition in bulk throughfall at DL (18.5 and 20.4 kg ha^{-1} yr^{-1}), a forest site downwind of metropolitan Mexico City, were significantly greater than at ZOQ (5.5 and 8.8 kg ha^{-1} yr^{-1}), a more distant site not directly exposed to the prevailing winds. However, more local sources may contribute to S deposition at ZOQ. Several plant and soil indicators suggest that N deposition at DL influences soil N availability and foliar N status. Sulfur deposition appears to also affect plant S concentration, although not to the same degree as N. Nitrate concentrations in 50% of the streamwater samples from DL were $\geq$ 15 μEq L^{-1}, demonstrating significant export of excess N from some watersheds. At ZOQ, 75% of the streamwater samples contained < 10 μEq L^{-1} NO_3^-. These findings suggest that atmospheric deposition of N has resulted in N saturation of the forest at DL. However, the severity of N saturation and the geographic extent of N saturation symptoms in forests within the Valley of Mexico is not known, and needs further study.

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Figure Captions

Fig. 1. Map showing the location of the two study areas.

Fig. 2. Cumulative bulk throughfall deposition of SO_4^{2-}, NO_3^-, and NH_4^+ and throughfall volumes at DL and ZOQ.

Fig. 3. Volume-weighted annual ion concentrations at DL and ZOQ. Error bars represent standard errors of the plot means. Letters above the bars indicate significant differences between site means.

Fig. 4. Average dry deposition fluxes to paper filter disks at forested sites southeast (Papayo) and southwest (Desierto) of Mexico City. Error bars are standard errors of the site means.

Fig. 5. Ionic concentrations in aqueous extracts of soil sampled at two depths in March and December 1996. No NH_4^+ was detected in soil at either site in December, 1996. Error bars represent standard errors of the plot means. Letters above the bars indicate when ion concentrations were significantly different between DL and ZOQ for the corresponding sample date and soil depth.

Fig. 6. Nutrient concentrations and ratios in current-year and one-year old foliage. Error bars and letters are as described for Figure 3.

Fig. 7. Scatter plot of concentrations of NO_3^- and SO_4^{2-} in streams at DL and ZOQ.

TABLE I

Characteristics of the two study sites

Characteristic	Desierto de los Leones	Zoquiapan
Altitude	3,325 m	3,350 m
Latitude[a]	19° 11' 18" - 19° 19' 42"	19° 12' 30" - 19° 20' 00"
Longitude[a]	99° 15' 00" - 99° 23' 00"	98° 42' 30" - 98° 30' 00"
Overstory vegetation	Pine and fir mix	Pine and fir mix
Understory vegetation	Predominantly pasture grasses: *Festuca, Muhlembergia, Stipa and Calamagrostis*	Predominantly pasture grasses: *Festuca, Muhlembergia, Stipa and Calamagrostis*
Stand age	20 - 40 years	40 - 60 years
Soil type	Humic Andisol, ochric	Mollic Andisol, humic
Forest fire history	Fires are suppressed in the park	Both controlled and unregulated fires occur
Annual precipitation[b]	146 cm	78 cm
Climate	Temperate subhumid with summer rain season and winter dry season	Temperate subhumid with summer rain season and winter dry season

[a]Latitude and longitude are for the entire Desierto de los Leones National Park, and for the Zoquiapan Experimental Forest (Blanco-Zavala *et al.*, 1981).

[b]Precipitation data not available for DL and ZOQ. Values given are throughfall volumes from this study for March 1996 to March 1997.

TABLE II

Nutrient concentrations[a] and pH of soil from DL and ZOQ

Site	Nutrient Concentration (g kg^{-1}) Sulfur	Carbon	Nitrogen	C:N Ratio	pH
		March 1996, 0-15 cm Depth			
DL	0.44	91.9 a	6.1 a	15.2	4.51
ZOQ	0.37	66.1 b	4.4 b	15.2	4.54
		March 1996, 15-30 cm Depth			
DL	0.42	74.7 a	4.9 a	15.3	4.53
ZOQ	0.37	48.6 b	3.2 b	15.4	4.57
		December 1996, 0-15 cm Depth			
DL	0.58 a	78.7 a	4.9 a	16.0	---
ZOQ	0.50 b	60.9 b	3.7 b	16.5	---
		December 1996, 15-30 cm Depth			
DL	0.53	64.4 a	4.0 a	16.1	---
ZOQ	0.47	47.3 b	2.9 b	16.7	---

[a]Letters following nutrient concentrations indicate significant differences ($p \leq 0.10$) between DL and ZOQ.

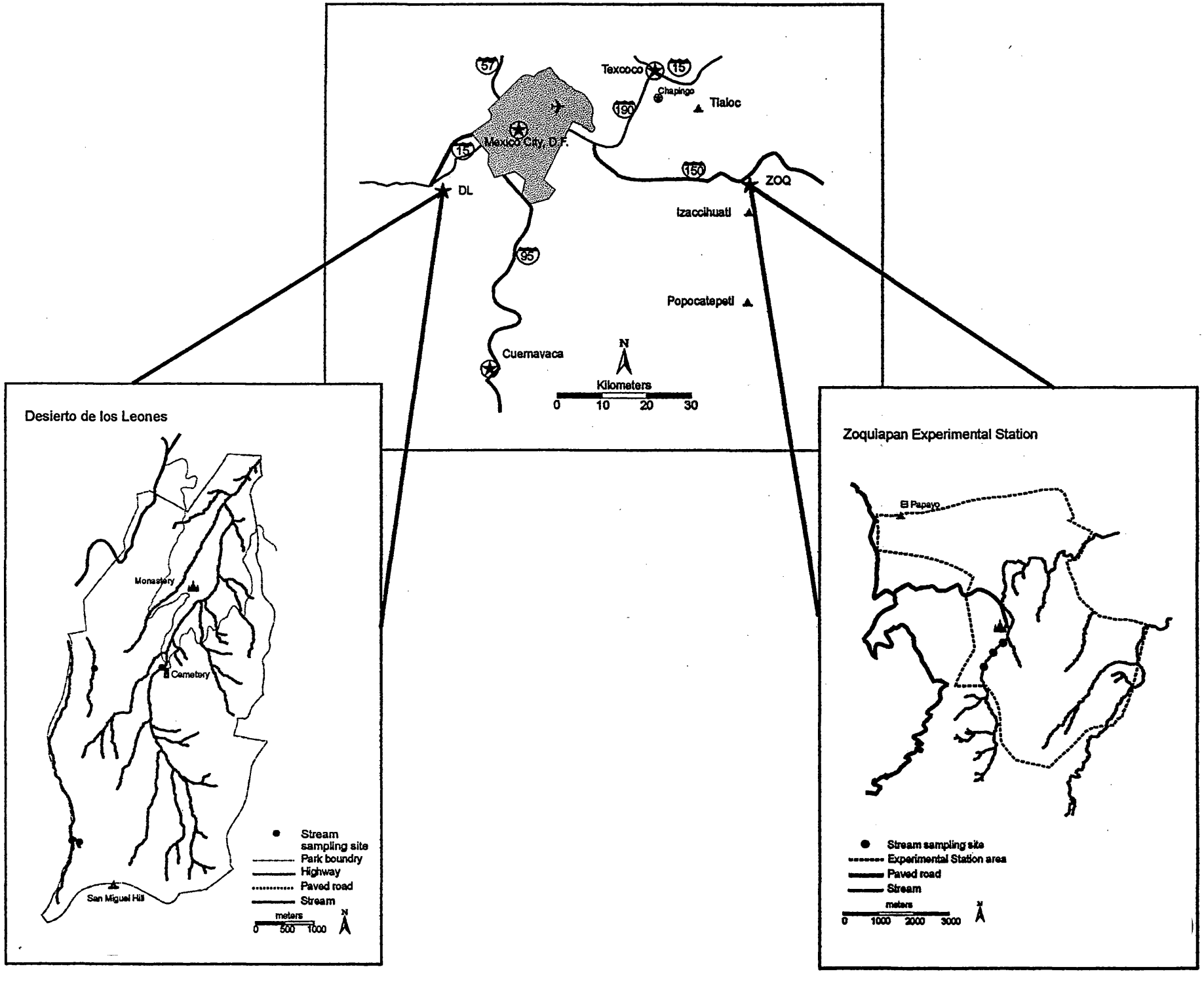

57
Texcoco
15
Chapingo
Tlaloc
190
Mexico City, D.F.
15
150
ZOQ
DL
Izaccihuatl
95
Popocatepetl
Cuernavaca
N
Kilometers
0 10 20 30
Desierto de los Leones
Monastery
Cemetery
San Miguel Hill
Stream sampling site
Park boundry
Highway
Paved road
Stream
meters
0 500 1000
N
Zoquiapan Experimental Station
El Papayo
Stream sampling site
Experimental Station area
Paved road
Stream
meters
0 1000 2000 3000
N

Fig. 1

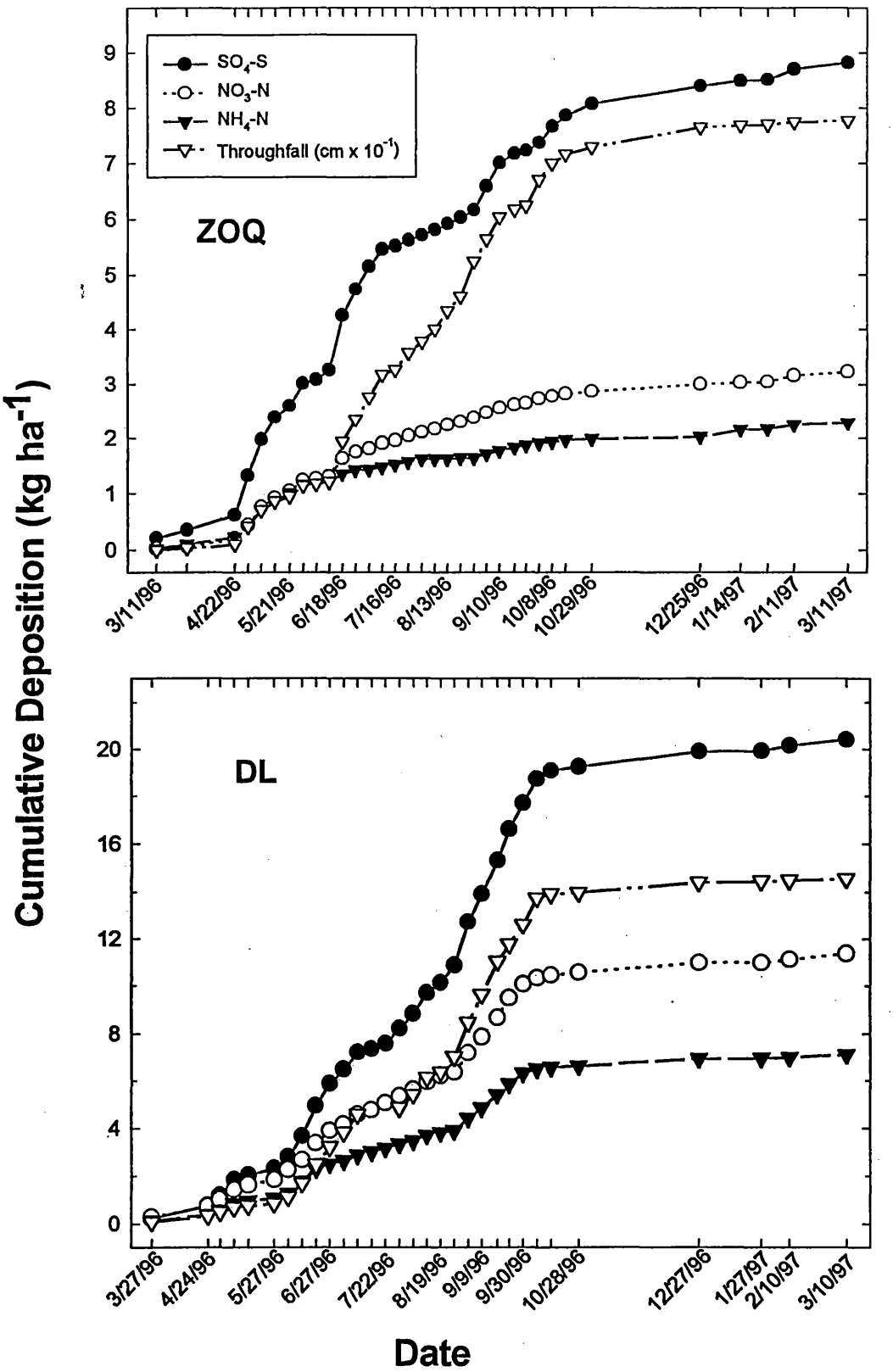

Cumulative Deposition (kg ha-1)
SO4-S
NO3-N
NH4-N
Throughfall (cm x 10-1)
ZOQ
DL
Date
3/11/96
4/22/96
5/21/96
6/18/96
7/16/96
8/13/96
9/10/96
10/8/96
10/29/96
12/25/96
1/14/97
2/11/97
3/11/97
3/27/96
4/24/96
5/27/96
6/27/96
7/22/96
8/19/96
9/9/96
9/30/96
10/28/96
12/27/96
1/27/97
2/10/97
3/10/97

Fig. 2

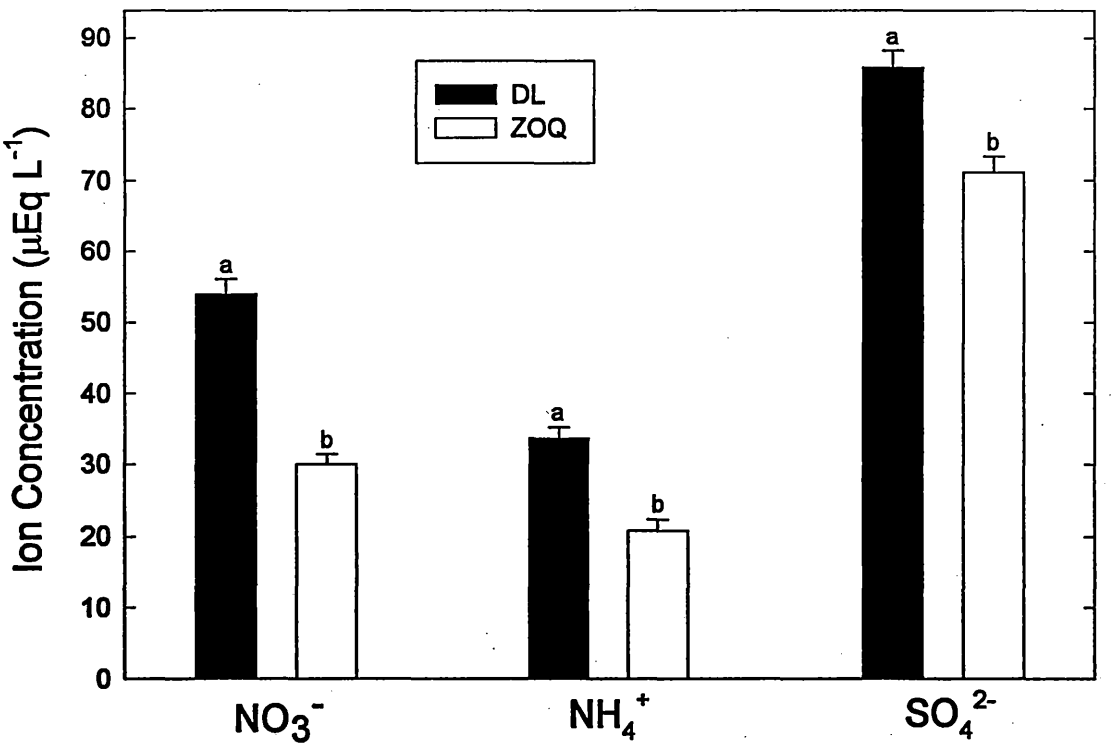

Ion Concentration (µEq L-1)
90
80
70
60
50
40
30
20
10
0
DL
ZOQ
a
b
a
b
a
b
NO3-
NH4+
SO4 2-

Fig. 3

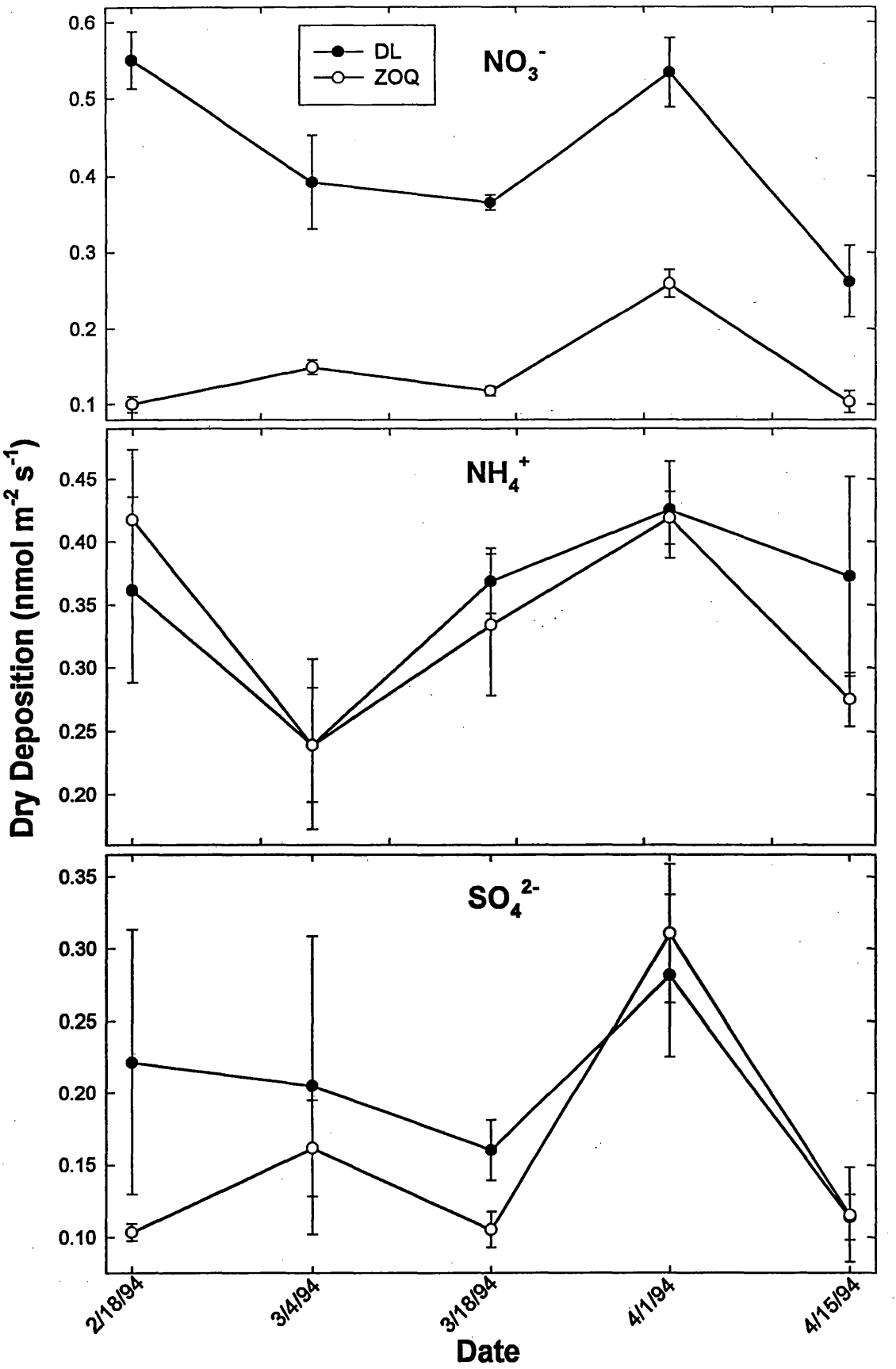
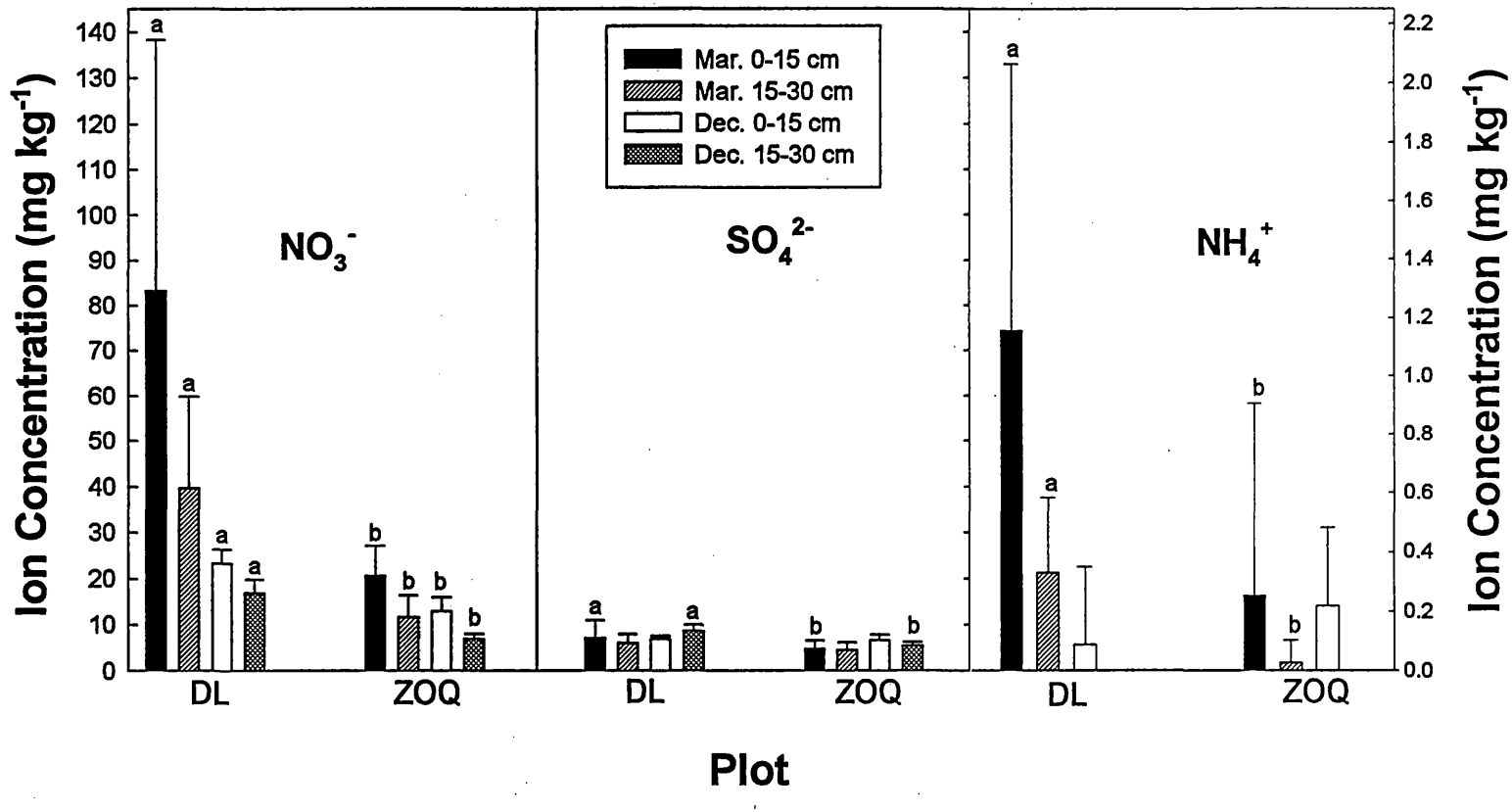

DL
ZOQ
NO_3^-
NH_4^+
SO_4^{2-}
Dry Deposition (nmol m^{-2} s^{-1})
0.6
0.5
0.4
0.3
0.2
0.1
0.45
0.40
0.35
0.30
0.25
0.20
0.35
0.30
0.25
0.20
0.15
0.10
2/18/94
3/4/94
3/18/94
4/1/94
4/15/94
Date

Fig. 4

Fig. 5


Mar. 0-15 cm
Mar. 15-30 cm
Dec. 0-15 cm
Dec. 15-30 cm
NO_3^-
SO_4^{2-}
NH_4^+
Ion Concentration (mg kg^{-1})
Ion Concentration (mg kg^{-1})
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
a
a
a
a
b
b
b
b
a
a
a
a
b
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a
b
b
b
b
DL
ZOQ
DL
ZOQ
DL
ZOQ
Plot

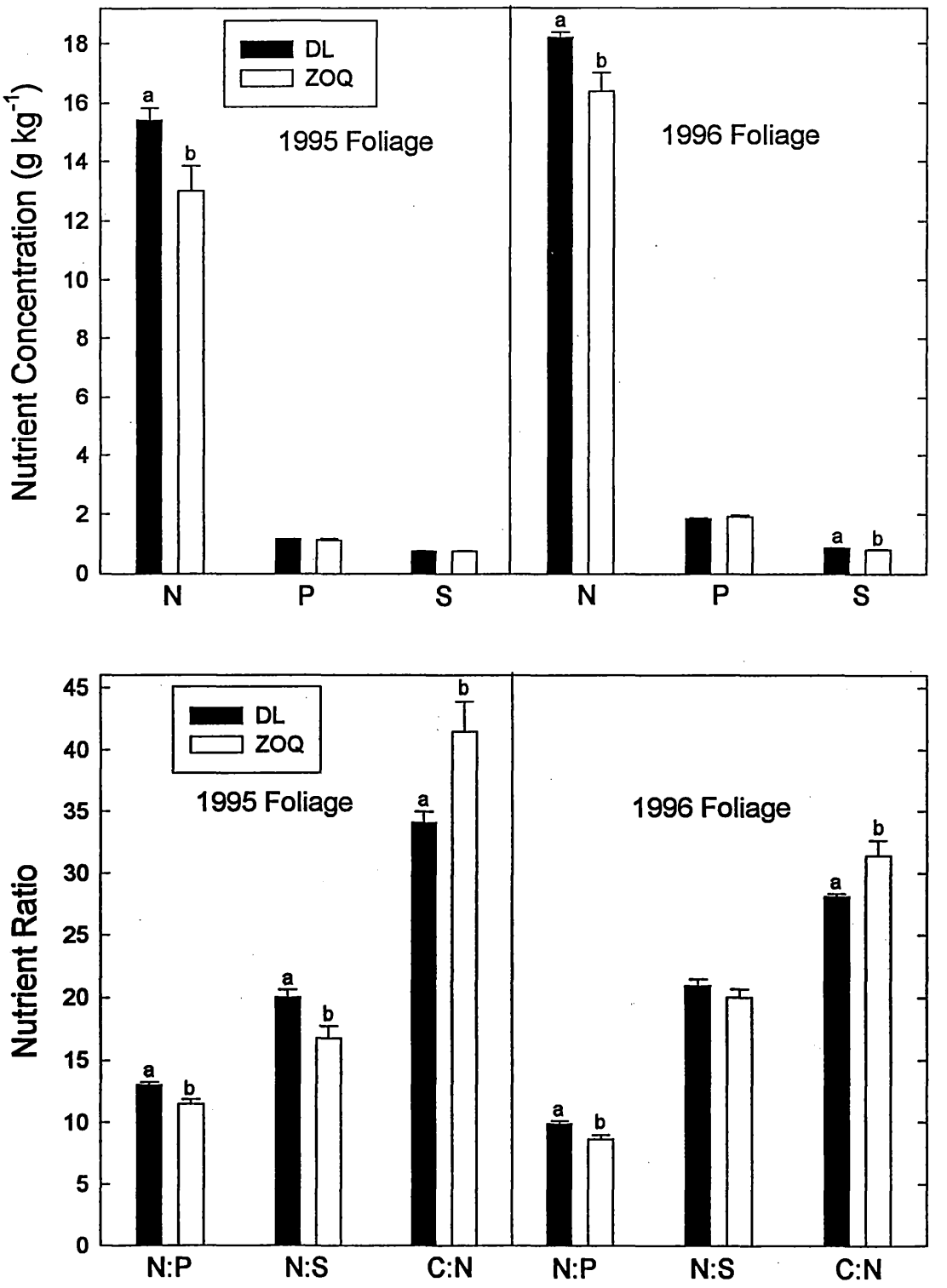
Nutrient Concentration (g kg-1)
DL
ZOQ
1995 Foliage
1996 Foliage
N
P
S
Nutrient Ratio
N:P
N:S
C:N

Fig. 6

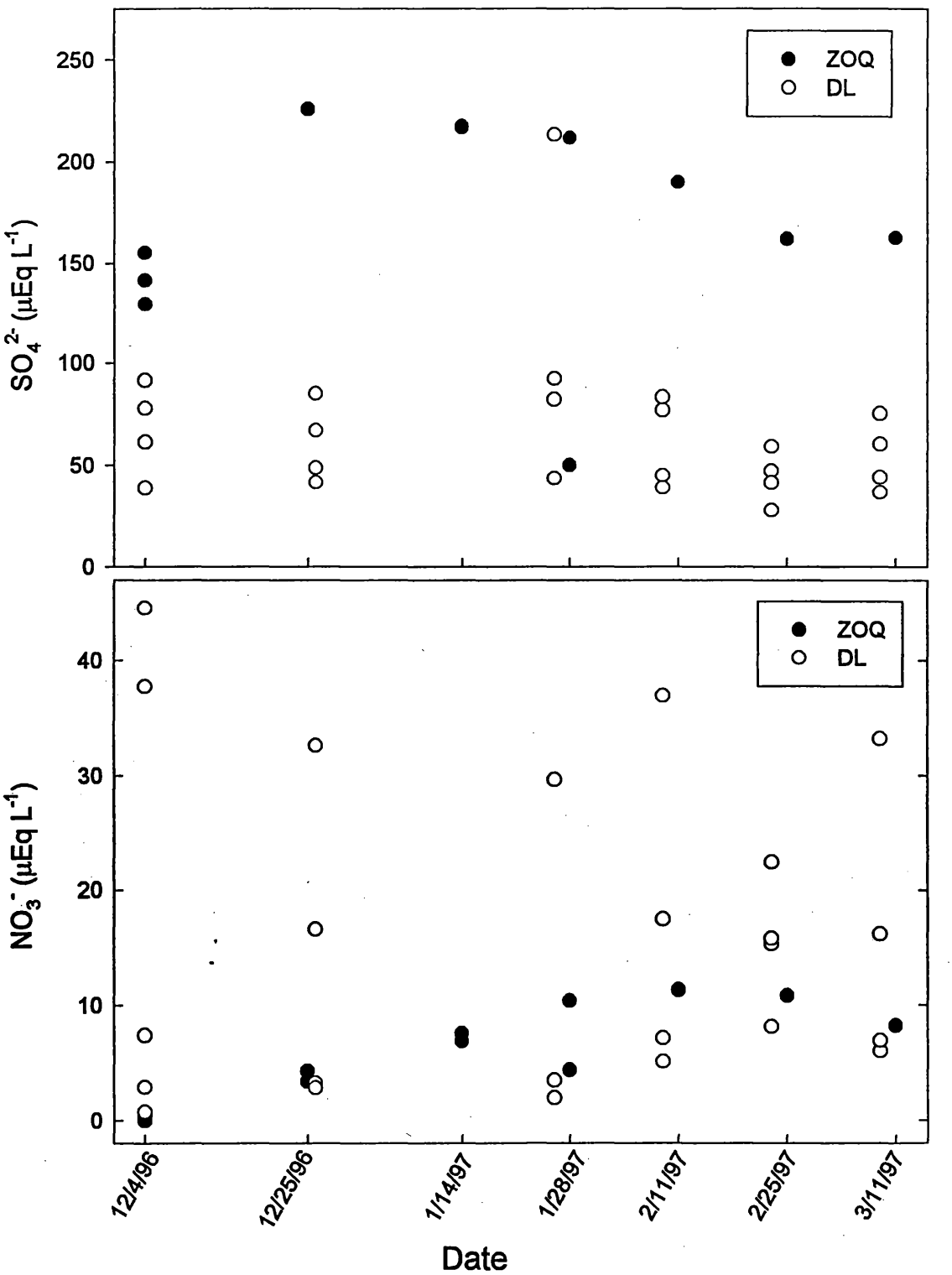
ZOQ
DL
250
200
150
100
50
0
SO_4^{2-} (µEq L^{-1})
ZOQ
DL
40
30
20
10
0
NO_3^- (µEq L^{-1})
12/4/96
12/25/96
1/14/97
1/28/97
2/11/97
2/25/97
3/11/97
Date

Fig. 7